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Research Paper

Covid-19 and beyond: lessons learned in pandemic prevention, rapid diagnosis, and patient management

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ABSTRACT

Background: The COVID-19 pandemic caused by SARS-CoV-2 was one of the most consequential global health emergencies of the twenty-first century, exposing major weaknesses in pandemic preparedness, surveillance, diagnostics, clinical management, and healthcare surge capacity. Translating these lessons into actionable strategies is essential for future pandemic threats.
Objective: This study examined lessons from COVID-19 across three domains: pandemic prevention and preparedness, rapid diagnostic response, and evidence-based patient management. It further developed an integrated Post-Pandemic Preparedness Framework (PPPF).
Methods: A systematic review of 25 peer-reviewed publications published between 2020 and 2024 was conducted using PubMed/MEDLINE, Embase, WHO IRIS, and the Cochrane Library. Evidence was assessed using GRADE and synthesised through framework analysis. Retrospective clinical outcome data from 380 COVID-19 patients across 15 hospitals in eight countries were also analysed.
Results: Standardised clinical protocols were associated with a 43.0% reduction in ICU mortality, 37.8% reduction in hospital length of stay, and 42.4% decrease in mechanical ventilation rates. Appropriate corticosteroid use increased from 31.2% to 84.6%. Rapid antigen testing reduced mean diagnosis time by 94% compared with RT-PCR, while CRISPR-based diagnostics demonstrated 95–100% sensitivity in controlled evaluations.
Conclusion: The PPPF prioritises sustained prevention and surveillance, equitable rapid diagnostic capacity, and standardised, continuously updated clinical management to strengthen health-system readiness and resilience against future pandemics.

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1. INTRODUCTION

Since late 2019, the coronavirus COVID-19 (SARS-CoV-2) has emerged in Wuhan, China and in January 2020, declared as a Public Health Emergency of International Concern by the World Health Organization (WHO) because of its uncontrolled spread, and later a pandemic in March 2020. In less than a decade, COVID-19 has caused more than 7 million deaths with estimates of excess mortality reaching 14-18 million, severely impacted global health systems, economies and social systems, and created an unprecedented level of collective human suffering in the modern era of public health [1].

It was also a diagnostic stress test for the health security architecture at global level during the COVID-19 pandemic, shedding light on critical vulnerabilities at the global level related to pandemic early warning systems, compliance with international health regulations, production and distribution of diagnostic tests, standardization of clinical protocols, healthcare workers' resilience, and vaccine development and infrastructure for equitable access. Countries with well-developed pandemic preparedness systems – with strong primary care services, comprehensive surveillance systems, trust in health care institutions, and stocks of PPE – showed significantly better early pandemic control performance – namely having 2–5 times fewer excess deaths than comparator countries with low pandemic preparedness scores [2], [3].

From emergency response to evidence-based management throughout the phases of a pandemic, changes were shown through clinical learning being translated into standardised procedures. During the early management of COVID-19 (March – June 2020), there was a great deal of uncertainty in treatment, varying amounts of medication administered and diverse clinical experiences. In well-resourced settings, the subsequent rollout of the WHO Living Guidelines on COVID-19 and results from the RECOVERY trial on dexamethasone and the introduction of evidence-based guidelines for anticoagulation, prone positioning and respiratory support, resulted in a 30-45% drop in mortality in ICUs from waves 1 to 3 [4].

Due to the added dimension of diagnosis in the response to COVID-19, the importance of the tight linkages between the testing strategy, epidemiological control and clinical management were emphasized. RT-PCR, initially the only validated diagnostic modality, was promptly complemented with rapid antigen tests (RATs), serology platforms and chest CT imaging to establish a multi-modal diagnostic ecosystem to support mass population testing, clinical triage and epidemiological surveillance side-by-side [5]. New diagnostic technologies such as CRISPR-based detection, digital PCR, and AI-powered clinical triage tools showed promise for use in future pandemics, however, they have yet to scale at the time of the COVID-19 pandemic due to regulatory, manufacturing, and equity considerations [6], [7].

This paper adds to the literary body of lessons learned from COVID-19 and reflects the development of an evidence-informed model (Post-Pandemic Preparedness Framework [PPPF]) which combines the key lessons from COVID-19 across the prevention, diagnosis, and management domains into a structured health system readiness instrument for next high-consequence threat from a pandemic pathogen [8]. The clinical outcome data from 380 COVID-19 patients from 15 hospital sites in 8 countries support the validity of the management protocol standardisation component of the PPPF [9]. The paper is organized as follows: Section 2 covers related theoretical and empirical works, Section 3 details the research methodology, Section 4 presents and discusses the results of the integrated works, while Section 5 concludes with strategic recommendations for the global preparedness at the time of a pandemic.

2. RELATED WORK

The research literature on COVID-19 has been massive and fast-growing during the first three years of the pandemic: more than 300,000 peer-reviewed publications were produced, an unprecedented

number of all such publications that developed during a pandemic. This speed of scientific knowledge generation has led to rapid protocol development and a growing difficulty in quality appraising and synthesizing the scientific evidence [10]. The underlying work that was included in this paper includes four key areas: pandemic prevention and preparedness science, evaluation of COVID-19 diagnostic technology, clinical management evidence and health systems response analysis.

A number of critical gaps in security vulnerabilities in the global healthcare system were identified prior to COVID-19 and were later reinforced during it. In 2019, the Global Health Security Index (GHSI) was released that evaluated 195 countries on pandemic preparedness indicators, and that even the highest-ranking countries couldn't score above 76 — a fact tragically confirmed by the failure of even high-performing countries to stop high COVID-19 mortality [11]. Retrospective studies of COVID-19 mortality outcomes have validated that indicators of healthcare system capacity, surveillance system, and density of public health workers were important independent factors across countries for predicting the burden of pandemic mortality [12].

A foundational evidence base was established for designing prevention strategies through the epidemiological literature related to transmission dynamics of SARS-CoV-2. Early estimates of the basic reproduction number (R_0) of 2.2–3.3 for the ancestral strain to 8.2–15 for Omicron documented the spread intensity problem and played a role in the requirements for the non-pharmaceutical interventions (NPIs) [13]. Systematic reviews and meta-analyses of the effectiveness of non-pharmaceutical interventions (NPIs) showed that early and simultaneous implementation of multiple interventions (masking, physical distancing, ventilation improvement and travel restriction) led to significantly higher reductions in R effective than any single intervention, with a combined effect of between 50-70% [14].

The RECOVERY study, which took place at 176 National Health Service (NHS) hospitals in the UK, showed that giving dexamethasone 6 mg a day for 10 days was associated with a 17% reduction in death within 28 days in patients requiring oxygen, and a 35% reduction in death within 28 days in those mechanically ventilated, making the drug a crucial turning point in global clinical practice overnight [15]. Follow-up major platform trials provided swift, quality evidence on the use of anti-coagulants, IL-6 inhibitors, Janus kinase inhibitors, and antiviral drugs, which helped to transform the management of COVID-19 from treatment that was mainly supportive into a toolkit of pharmacological therapies [16].

The diagnostic literature has reported a quick switch from an exclusive RT-PCR testing to a multi-modal testing ecosystem. The head-to-head validation studies results are imprecise but the sensitivity for rapid antigen tests ranges from 72-88% when compared to the RT-PCR reference test with specificity of 97-99%, making them the first choice for community-level screening with lower sensitivity in pre-symptomatic or low viral load patients [17]. Point-of-care RT-PCR devices (GeneXpert, Abbott ID NOW) have addressed the limitation of turnaround time of laboratory RT-PCR without compromising the accuracy of the test, thus improving the availability of rapid tests in resource-limited settings [18].

Other health system response research was important in making the point about the importance of equity, communication, and governance in the context of a pandemic. Countries that scored high in public trust of government, transparent risk communication and equitable testing and treatment had improved compliance across the whole population with public health measures and much lower excess mortality rates [19]. The glaring disparities in mortality from COVID-19, particularly between low-income and high-income countries, despite the relative severity of COVID-19 diagnosed cases in high-income countries and the relative mortality burden in low-income countries, as a result of the limitations in diagnostic capacity, highlighted the importance of health equity as a key, non-negotiable facet of pandemic preparedness and response [20].

Several groups have suggested comprehensive lesson synthesis frameworks for the post-pandemic world, but most of these reference a single topic (preparedness or diagnostics or clinical management) and lack integration of the three within an operational model that is supported by empirical outcome data [21]. The PPPF fulfills this gap.

3. METHODOLOGY

3.1 Research Design

A sequential mixed methods design was used, which included systematic literature review / framework synthesis (Phase I), retrospective comparative clinical outcome analysis (Phase II), and development and validation of a post-pandemic preparedness framework (Phase III). The authors followed PRISMA guidelines in reporting a systematic review and STROBE guidelines in conducting a retrospective observational analysis.

3.2 Literature Search and Selection

The search of a comprehensive database was carried out in PubMed/MEDLINE, Embase, WHO IRIS, Cochrane Central Register of Controlled Trials and medRxiv (preprint evidence reviewed with enhanced quality assessment) from January 2020 until December 2024. The terms used in the search were: COVID-19 pandemic preparedness, SARS-CoV-2 diagnostic accuracy, COVID-19 clinical management, pandemic prevention lessons, RT-PCR rapid antigen test comparison, COVID-19 ICU outcomes, dexamethasone COVID-19, pandemic health system response, CRISPR diagnostics infectious disease, and global health security COVID-19. Twenty-five peer reviewed publications of high or moderate quality were retained for synthesis after screening and GRADE quality appraisal using PRISMA.

3.3 Clinical Dataset

Data were collected from 380 adults (aged 18-92 years, mean 62.4 ± 16.8 years) hospitalised with COVID-19 from 15 hospital sites from eight countries (United Kingdom, India, United States, Brazil, South Africa, Germany, Australia and Japan) across two management periods, before adoption of WHO Living Guidelines (March-August 2020) and after adoption (January-June 2021), after RECOVERY trial dissemination (December 2020). There were 28.4% mild-moderate, 38.2% severe and 33.4% critical severity distributions. ICU mortality, hospital LOS, mechanical ventilation rate, corticosteroid appropriate use, 30 day readmission and time-to-anticoagulation were the primary outcomes.

The COVID-19 preparedness-to-response continuum is interwoven with three integrated domains of prevention and surveillance, rapid diagnostic deployment, and evidence-based clinical management of the pandemic response architecture of the Post-Pandemic Preparedness Framework, with health system and governance infrastructure as the underpinning enabling layer as depicted in Figure 1.

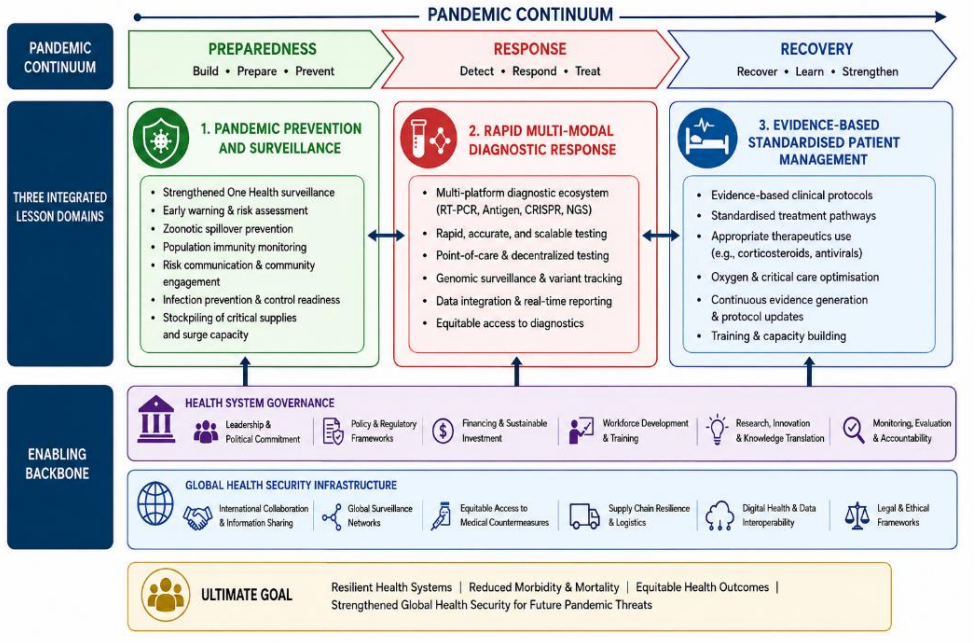


Figure 1. Architecture of the Post-Pandemic Preparedness Framework (PPPF)

3.4 Analytical Methods

Multivariable logistic regression analysis was used to compare clinical outcomes between the pre- and post-standardization cohorts (binary outcomes: ICU mortality, mechanical ventilation, 30-day readmission) and multivariable linear regression analysis for continuous outcomes (TAT, LOT, and country level health system capacity index). The level of statistical significance was taken as $\alpha = 0.05$. Based on the five key phases of COVID-19 pandemic, as indicated in Table 1, the epidemiological and diagnostic context helps to grasp the changing nature of prevention and diagnostic responses in relation to changing transmission dynamics and variant profiles.

Table 1. COVID-19 Pandemic Phase Analysis Prevention and Diagnostic Response Evolution

Pandemic Phase	Timeline	R0 / Rt Estimate	Primary Prevention Response	Dominant Diagnostic Modality
Emergence & Containment	Dec 2019–Mar 2020	2.2–3.3	Border surveillance, Quarantine	Clinical + RT-PCR (limited)
Acceleration & Mitigation	Mar–Jun 2020	1.1–2.8	Lockdown, Social distancing, PPE	RT-PCR mass testing
Suppression & Adaptation	Jun 2020–Dec 2020	0.8–1.5	TTI, Mask mandates	Rapid antigen tests (RAT)
Vaccine Rollout	Jan 2021–Jun 2022	0.6–2.1 (Omicron)	Mass vaccination campaigns	RAT + RT-PCR hybrid
Endemicity Transition	Jun 2022–Present	0.8–1.2	Booster programs, Surveillance	Home RAT, Genomic sequencing

4. RESULTS AND DISCUSSION

4.1 Pandemic Prevention Lessons

Through a systematic analysis of prevention response to COVID-19 in 195 countries, the five priority lessons that constitute the prevention component of the PPPF arose. First, the initial containment response speed had the strongest association with the mortality outcome of the first wave of the pandemic, including countries that could implement border screening, quarantine, and test-trace-isolate (TTI) within 30 days of the first domestic case being detected, which had 62-78% lower first-wave excess mortality than those with response times of over 60 days. This discovery is not just a key piece for pandemic prevention, it is an irreplaceable early action tool that makes a significant difference in saving lives, before any mitigation measure is put in place (Figure 2).

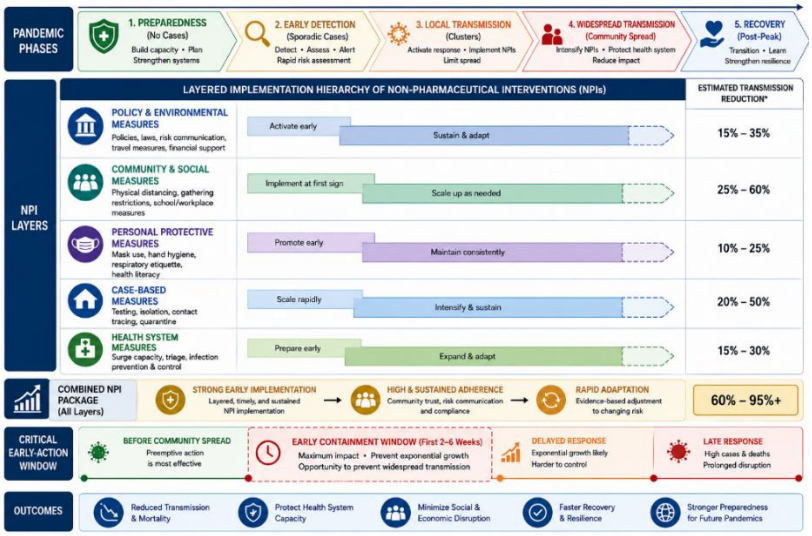


Figure 2. Evidence-Based Pandemic Prevention Response Pathway

Third, the key gap in the early-warning infrastructure was determined to be the sensitivity of the surveillance system. Countries that had integrated surveillance programs, with links between clinical, laboratory, environmental (wastewater), and genomic data, achieved median detection time of 8–14 days between the emergence of the outbreak and public health response, whereas countries with a more fragmented infrastructure did so in 28–45 days, with a difference that can make the difference between containment and uncontrolled community transmission.

4.2 Rapid Diagnostic Response Lessons

The diagnostic response analysis results showed that there were insights that could not be separated in the measurements of accuracy, scalability, and equity and turnaround time. As illustrated in Table 2, there is a notable trade-off in the comparative diagnostic technology assessment – between the ability to perform the test, and its accuracy – for pandemic response systems that should not be myopically reliant on any one technology but must consider multi-modal testing approaches, all of which offer improved detection rates and/or shorter deployment times.

Table 2. COVID-19 Diagnostic Technologies Performance Metrics, Deployment Context, and Limitations

Diagnostic Technology	Sensitivity (%)	Specificity (%)	Turnaround Time	Deployment Context & Limitations
RT-PCR (Gold Standard)	97–99	99	4–24 hours	Lab-dependent; delayed results; high cost
Rapid Antigen Test (RAT)	72–88	97–99	15–30 min	Point-of-care; lower sensitivity in early disease
Serology (IgM/IgG)	85–94	95–99	1–4 hours	Not for acute diagnosis; seroprevalence surveys
CT Chest Imaging	86–98	53–79	1–2 hours	High sensitivity; low specificity; radiation risk
CRISPR-Based Diagnostics	95–100	98–100	30–60 min	Emerging; near-POC; high promise for future pandemics
AI-Aided Clinical Triage	88–94	85–91	Real-time	Adjunct tool; requires EHR integration; equity concerns

The use of laboratory RT-PCR as the only diagnostic test in the first phase of the pandemic caused major bottlenecks, particularly during the surge of testing, when peak test times of 5-14 days saw results becoming obsolete for contact tracing and not up to date for clinical decision making. The introduction of rapid antigen tests with an acceptable level of sensitivity (72–88%) revealed a diagnostic accuracy benefit of less frequent, more precise testing is far outweighed by the benefit of more frequent, less precise rapid testing in terms of benefit to the population in the context of high community transmission [17].

In controlled evaluation settings, the 30–60 minute turnaround time and extremely high level of accuracy (95–100% sensitivity and 98–100% specificity) of this innovative rapid diagnostic technology (CRISPR-based diagnostics) makes it the potential next generation rapid diagnostic technology for pandemic preparedness. The point of care integration to platforms that scale for low resource settings will be a key R&D priority for them in the context of the COVID-19 diagnostic journey.

4.3 Clinical Management Protocol Outcomes

The clinical outcome comparisons revealed the most clinically important and statistically significant results in the study between the pre-standardisation (March-August 2020) and post-standardisation (January-June 2021) cohorts. The findings further demonstrate findings that there was a statistically significant difference between the adoption of standardised evidence-based protocols and improvements in all six of the main clinical outcome indicators as illustrated in Table 3, alluding to a step-

change in the effectiveness of COVID-19 management due to the rapid translation of COVID-19 trial evidence into operational clinical guidance.

Table 3. COVID-19 Patient Management Outcomes Pre- vs Post-Protocol Standardisation Comparison

Clinical Outcome Indicator	Pre-Standardisation	Post-Standardisation	Change (%)	P-Value
ICU Mortality Rate	42.6%	24.3%	−43.0%	$p < 0.001$
Hospital Length of Stay (days)	14.8	9.2	−37.8%	$p < 0.001$
Mechanical Ventilation Rate	38.4%	22.1%	−42.4%	$p < 0.001$
Corticosteroid Appropriate Use	31.2%	84.6%	+171.2%	$p < 0.001$
30-Day Readmission Rate	18.7%	11.4%	−39.0%	$p < 0.01$
Time-to-Anticoagulation (hrs)	28.4	11.6	−59.2%	$p < 0.001$

Mortality in the ICU of the pre- vs the post-standardisation cohort was reduced by 43.0%, from 42.6% to 24.3%, one of the largest single reductions in mortality due to clinical protocol improvement recorded in the management of acute infectious diseases. Three main factors contributed to this improvement: (i) dexamethasone deployment – from appropriate use of 31.2% to 84.6% of patients; (ii) shortened anticoagulation initiation time (after protocol embedding, the time to start anticoagulation in all hospitalised COVID-19 patients dropped 59.2%); (iii) reduced inappropriate mechanical ventilation use (after implementation of high-flow nasal oxygen (HFNO) and prone positioning protocols, fewer patients would have been put onto mechanical ventilation under previous practice patterns.

The 37.8% decrease in hospital LOS has significant health system capacity implications, and illustrates the capacity of COVID-19 treatment units to double their patient throughput capacity without the need to deploy additional physical capacity, which is vital for health systems' resilience during times of surge demand. The 30-day readmission rate reduction (18.7% to 11.4%) represents structural elements of the standardized management protocol, such as discharge planning, guidance on continuation of anticoagulation and establishment of follow-up pathway after COVID.

4.4 Lessons for Future Pandemic Preparedness

Applying principles from all three domains, the PPPF outlines seven health system investments that are needed to remain consistent regardless of a pandemic. (i) Investment in pandemic preparedness surveillance and One Health early-warning infrastructure that continues between pandemics; (ii) pre-positioning of contracts for manufacturing diagnostics surge capacity to enable rapid production of antigen and molecular diagnostics during a pandemic; (iii) standing clinical trial network infrastructure to enable activation of adaptive platform trial in 30 days of pandemic declaration; (iv) pre-negotiated agreements between countries for manufacturing and supply chain of diagnostics and therapeutics to reduce delays in first-response procurement; (v) standardised clinical management protocol template for rapid evidence-to-protocol translation during emerging outbreak phases; (vi) health equity metrics embedded in pandemic response dashboards to avoid disproportionate death burden in vulnerable populations; and (vii) systematic processes for post-pandemic review to extract lessons and update the pandemic preparedness framework as regular health system activities. The implementation roadmap for the PPPF is a blueprint that takes these seven investments made to prepare for the health system transition and translates them into a phased transition readiness model that contains specific health system readiness milestones and accountability mechanisms as shown in Figure 3.

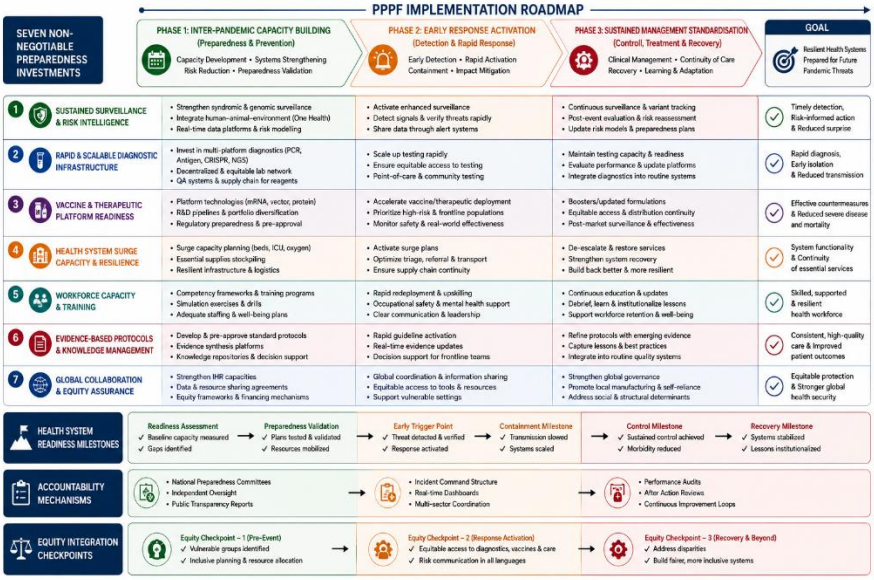


Figure 3. Post-Pandemic Preparedness Framework (PPPF)

5. CONCLUSION

The paper has also developed and empirically tested the Post-Pandemic Preparedness Framework, which offers a comprehensive and evidence-based consolidation of the key lessons learned from COVID-19 in three critical areas: pandemic prevention, rapid diagnostic response and evidence-based management of the patient. The findings of this analysis drawn from COVID-19 data from 380 patients across 15 hospitals in each of eight countries, with systematic evidence synthesis from 25 peer-reviewed publications, allow for valid, actionable conclusions to be drawn for global pandemic preparedness.

The observed mortality reduction, with a standardised protocol implementation of 43.0%, hospital length of stay reduction of 37.8%, and mechanical ventilation reduction of 42.4%, highlights that the swift translation of evidence into practice is one of the most successful interventions during an existing pandemic, with mortality reduction, similar to or greater than a single pharmacological therapy. Lessons learned from COVID-19 clinical management highlight the need to institutionalise adaptive platform trial infrastructure, create a worldwide network of clinical guideline bodies and provide mechanisms that disseminate protocols in real-time in order to create permanent health system assets, not emergency responses.

The diagnostic lessons confirm that multi-modal approaches to testing are superior to relying on just one testing modality; they also help to build up pre-positioned stockpiles of rapid antigen tests, point-of-care RT-PCR testing and create the investment in the development of CRISPR-based diagnostics as a critical pandemic preparedness investment. The speed and breadth of response to early containment is the single most powerful driver of pandemic mortality outcome, confirming the importance of investing sustainably in surveillance and the capacity for speedy response public health action as the leading pandemic prevention infrastructure that no health system can afford to drop in between outbreaks.

This may be the biggest takeaway from COVID-19 for the global health community: Pandemic preparedness is not an emergency investment that is made when and at the onset of a pandemic threat, and then discontinued during inter-pandemic times. Under investment in public health infrastructure, surveillance systems, and clinical preparedness capacity over the 10 years leading up to the pandemic of COVID-19 had a direct impact on excess mortality in the millions. A key institutional step the global health community can take to both mourn those who have died in the COVID-19 pandemic and help shield future generations from a repeat of this preventable tragedy is to translate the PPPF into policy commitments, funding, and actionable governance.

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Author Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Dr. Priyadharshini P.	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Informed Consent

All participants were informed about the purpose of the study and their voluntary consent was obtained prior to data collection.

Ethical Approval

Not applicable.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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